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Green Roofs Impact on Buildings Cooling Load

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ABSTRACT

Green roofs are being more and more promoted in south Europe. The main sales arguments are based on esthetic, depolution and thermal comfort.
This paper proposes a model of the heat and mass transfer phenomenon taking place in these roofs. An experimental validation of the model is performed and presented. Four types of roofs are studied; the varied parameter is the type of soil used for the vegetation and the thermal inertia of the roof itself.
The use of the developed model permits to conduct an analysis on the impact of the use of green roofs on buildings' cooling load. This analysis studies the green roof impact as a function of the location, the type of soil and the geometry of the building.

1. INTRODUCTION

Green roofs are being more and more promoted in south Europe. The main sales arguments are based on esthetic, depolution and thermal comfort (Barrio, 1998). The heat and mass transfer phenomenon taking place in these systems are acting as an efficient barrier against solar radiation permitting to phase out this load leading to reduced energy consumption for air conditioning and an improved thermal comfort (Alexandri, 2007). The most important phenomenon is the water evaporation and vegetation transpiration which can compensate the received solar radiation at almost constant temperature.
Many scientific studies explored the vegetation thermal behavior and tried to model its biological response (Duchaufour, 1995), (Pielke, 2002), (Vershinin, 1966). In particular, they modeled the transpiration phenomenon variation as a function of the soil humidity level and the radiative flux.
In this paper three types of green roofs are studied:

- Heavy roof with semi intensive culture;
- Heavy roof with extensive culture;
- Light roof with extensive culture;

These types represent the most common green roofs installed in France. The analysis methodology is based on both numerical modeling and experimental study.

2. Description of the green roofs structure

There are typically two types of green roofs: semi intensive culture, which have thick soil and can support a wider variety of plants but are heavier and require more maintenance, and extensive culture, which have a thin layer of soil and are lighter than an intensive culture. All green roofs are composed of the same basic components: a waterproof layer, a drainage layer, the soil layer and the vegetation layer. The type of vegetation set up on a roof depends essentially on the climate, the air moisture and the water content of soil. If the vegetation is not surviving through the seasons, some areas of the soil could be periodically naked. We introduce the LAI (leaf area index) and SN (soil nudity) factors to define the vegetation arrangement. The LAI (eq. 1) factor defines the leaf area per unit area of soil below it and the SN factor (eq. 2) defines the percentage of the naked soil as shown in Figure 1.

$$LAI = S_{leaf}/S_{projected} \quad (1)$$

$$SN = S_{naked}/S_{roof} \quad (2)$$

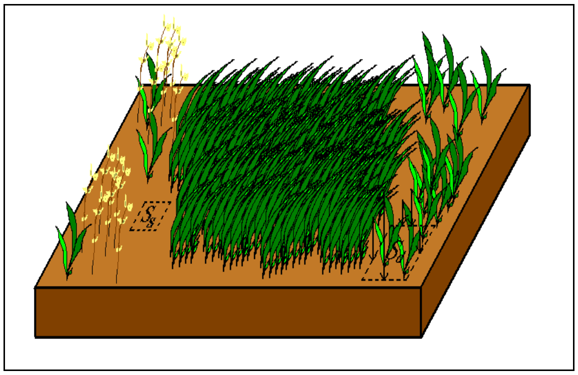
Figure 1: LAI and SN factors definition

The roofs solid structure are made either of concrete (for heavy roofs) or of steel (for light roofs). This structure must be able to hold the weight of the top layers. It is assumed that the solid structure is waterproof and the heat transfers are taking place by conduction only.

3. Green roof model description

3.1 Heat and mass transfer phenomenon

The heat and mass transfers which are taking place between the sun, the sky, the soil and the canopy are all presented in Fig.2. Radiative exchanges are represented by continuous lines and the mass transfers are represented by dotted lines.

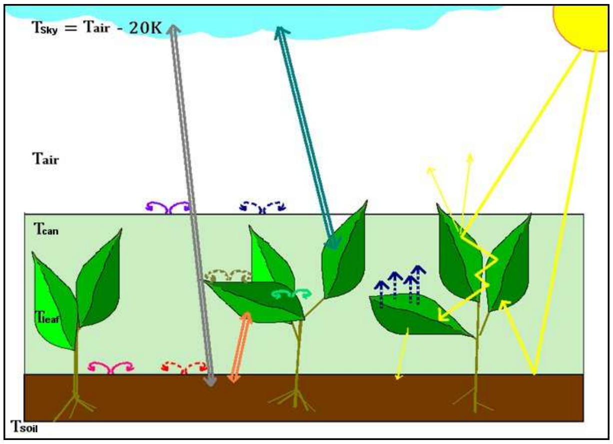

Figure 2: Heat and mass transfer phenomenon

The vegetation, the canopy and the soil of the green roof receive solar radiation φ_{sun}. In the infrared wavelength, the soil, the canopy, the sky and the vegetation exchange between each other radiative fluxes φ_{rad}. The vegetation leaves evaporate water through their stomata by transpiration. This process includes three phenomena: water evaporation inside the leaves, vapor diffusion to the leaves surface and convective vapor transport from the leaves surface and the air of the canopy. At the same time, water evaporates from the soil and is transferred to the surrounding ambiance by convection. Heat is also exchanged by convection exchange between the soil and the surrounding air and between the vegetation leaves and the surrounding air.

3.2 Mathematical formulation

It is assumed that the air surrounding the canopy is highly renewed because in the most of the cases, the vegetation on the green roofs is not tall and dense enough to create a micro climate. Consequently, the canopy air and ambient air have the same properties.

First of all, we will describe the model of the upper part of the system {outside air and vegetation}. The vegetation is considered as semi-transparent. The solar fluxes are at the same time, absorbed, transmitted, reflected and emitted. So the solar flux received by the vegetation is obtained by equation 3.

$$\varphi_{sun \rightarrow leaf} = \alpha^*_{leaf}\varphi_{sun} \tag{3}$$

The equivalent radiative properties of the vegetation is defined by Bario (1998) as written in equations 4-6.

$$\alpha^*_{leaf} = 1 - \rho^*_{leaf} - \tau^*_{leaf \leftrightarrow sun} = 1 - (1 - \tau^*_{leaf \leftrightarrow sun}) * 0,12 - \tau^*_{leaf \leftrightarrow sun} \tag{4}$$

$$\tau^*_{leaf \leftrightarrow sun} = \exp(-k_s * LAI) \tag{5}$$

$$\rho^*_{leaf} = (1 - \tau^*_{leaf \leftrightarrow sun}) * 0,12 \tag{6}$$

The radiative heat transfer occurring between the leaves and the sky are modeled by the equation 7.

$$\varphi_{sky \leftrightarrow leaf} = \alpha^*_{leaf}\sigma(T^4_{sky} - T^4_{leaf}) \tag{7}$$

Bario (1998) gives a simple correlation of the sky temperature (eq. 8).

$$T_{sky} = T_{air} - 20 \tag{8}$$

The convective heat transfer occurring between the leaves and the ambiant air are modeled by the equation 9.

$$\varphi_{conv,air \leftrightarrow leaf} = -h_{leaf}(T_{air} - T_{leaf}) \tag{9}$$

With:

$$h_{leaf} = \frac{LAI}{r_a}\rho_{air}c_{p_{air}} \tag{10}$$

The mass transfer due to the transpiration of the plant is modeled by the Pielke's equation 11 (Pielke, 2002).

$$\varphi_{transpiration,air \leftrightarrow leaf} = LAI * \frac{L_v(T_{leaf})}{r_{air \leftrightarrow leaf}} \frac{[P_{sat}(T_{leaf}) - HR * P_{sat}(T_{air})]}{R_{vap}T_{leaf}} \tag{11}$$

With:

$$r_{air \leftrightarrow leaf} = r_a + r_{sto} \tag{12}$$

$$r_{sto} = r_c\left(\frac{I_{max}}{0.03 * I_{max} + \varphi_{sun}} + \left(\frac{\omega_{wp}}{E_{soil}}\right)^2\right) \tag{13}$$

$$r_a = \frac{1}{0.01 * \left(1 + \frac{1}{V_{wind}}\right) * 0.3 * V_{wind}} \tag{14}$$

The soil humidity is assumed to vary between the wilting point $\omega_{wp} = 0.04$ and the field capacity point $\omega_{fc} = 0.25$. The wilting point is defined as the limit soil humidity that the vegetation can pump to live. And the field capacity point is defined as the limit of water absorbtion; above which water will drain from the soil. So the model is valid only if $\omega_{wp} \leq E_{soil} \leq \omega_{fc}$. Note that the stomata resistance r_{sto} and the wind resistance r_a are both strongly depending on the nature of the vegetation.

Secondly, we studied the system {soil and climate}. Some areas of the soil can be naked; therefore the soil receives solar flux and exchange radiative heat in the infrared, by:

$$\varphi_{sun\rightarrow soil} = \tau^{*}_{leaf\leftarrow sun}\left[\alpha^{*}_{soil} + \frac{1}{1-\rho^{*}_{soil}\rho^{*}_{leaf}}\right] * \varphi_{sun} \tag{15}$$

$$\varphi_{soil\leftrightarrow sky} = \sigma\varepsilon^{*}_{soil}\tau^{*}_{leaf}\left[T^{4}_{sky} - T^{4}_{soil}\right] \tag{16}$$

Moreover there are mass transfer between the soil and the ambient air.

$$\varphi_{evaporation,air\leftrightarrow soil} = R_{Lewis} * h_{air\leftrightarrow soil} * L_V(T_{soil}) * \frac{[P_{sat}(T_{soil}) - HR * P_{sat}(T_{air})]}{R_{vap} * \rho_{air} c_{p_{air}} * T_{soil}} \tag{17}$$

With R_{Lewis} a soil drying resistance taking into account partial drying of the surface and defined by Slim (2007)

$$R_{Lewis} = a - (1 - E_{soil}) * b \tag{18}$$

a and b depends of the soil nature.

The convective heat transfer between the soil and the air is represented by the equation (19)

$$\varphi_{conv,air\leftrightarrow soil} = h_{air\leftrightarrow soil}(T_{air} - T_{soil}) \tag{19}$$

With:

$$h_{air\leftrightarrow soil} = \frac{\rho_{air} c_{p_{air}}}{LAI * r_a} \tag{20}$$

The third and last system to study is {Soil and vegetation}. Between the soil and the vegetation there are infrared radiative heat transfer, modeled by equations 21 and 22.

$$\varphi_{rad,soil\rightarrow leaf} = \sigma\{(1 - \tau^{*}_{leaf-IR})\varepsilon^{*}_{soil}[T^{4}_{soil} - T^{4}_{leaf}] - \tau^{*}_{leaf-IR}T^{4}_{leaf}\} \tag{21}$$

$$\varphi_{rad,leaf\rightarrow soil} = \sigma\varepsilon^{*}_{soil}[T^{4}_{leaf} - T^{4}_{soil}] \tag{22}$$

It is assumed, in the infrared, that the reflection of vegetation and the soil is negligible.
The energy balance of each system components is written herebelow:

- Balance on the vegetation:

$$\varphi_{leaf} = \varphi_{leaf\leftarrow sun} + \varphi_{leaf\leftrightarrow sky} + \varphi_{soil\rightarrow leaf} - \varphi_{transpiration} \tag{23}$$

- Balance on the medium layer:

$$\varphi_{soil} = \varphi_{sun\rightarrow soil} + \varphi_{soil\leftrightarrow sky} + \varphi_{leaf\rightarrow soil} - \varphi_{evaporation} \tag{24}$$

4. Experimental validation

3 slab tests representing different green roofs are used for the model validation (figure 3): a semi-intensive and an extensive green roof with a concrete structure (heavy roof), and an extensive green roof with a steel structure (light roof).

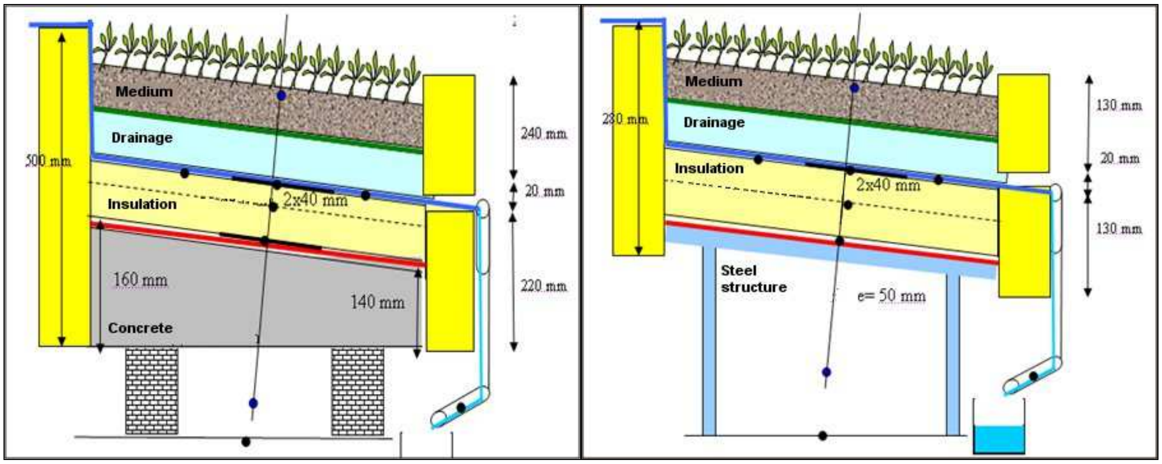

Figure 3: Scheme of heavy and light systems used for the experimental validation

Sensors have been used to measure the solar flux received by the vegetation and the soil, the temperature of the ambient air, the velocity of the wind close to the vegetation and the ambient air relative humidity. Within the experimental roofs, temperatures are measured at each layer as represented by the points in figure 3. One or two fluxmeters are also used to determine the heat flux intensity and direction within the roof. In the case of light roof, only one fluxmeter is used on the top of the insulation layer. For the heavy structure, two fluxmeters are used one on the top of the insulation layer and the second one on the top of the concrete layer.

The measures have been recorded during 7 days with an interval of time of 5 minutes. In the following, the blue curves illustrate the simulation results and the red dotted curves illustrate the experiment results (in Kelvin). Note that at the end of the first day of the experience, it has rained.

4.1. Semi-intensive green roof with a concrete structure

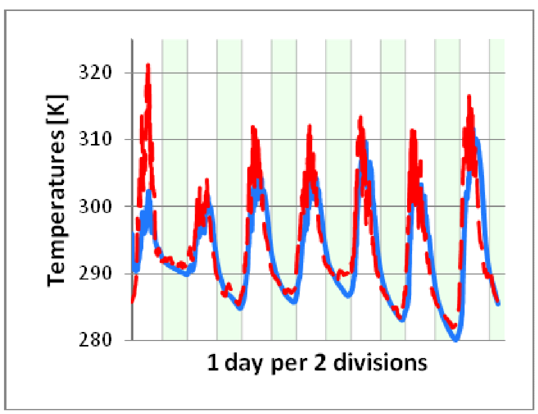

Figure 4: temperature on top of the soil layer- heavy roof, semi intensive vegetation

Figure 4 shows the temperature measured and calculated on the top of the soil layer. The measurements show, that after a high temperature increase in the first day at noon, the soil temperature increase at noon in the following days is relatively small. This is due to the rain that occurred at the end of the first day resulting in soil humidity saturation. Following the second day, a trend of maximal temperature increase is observed. This has been also represented by the model. This trend is explained by the humidity decrease in the soil which reduces the transpiration phenomenon. The partial surface drying is also participating to this trend.

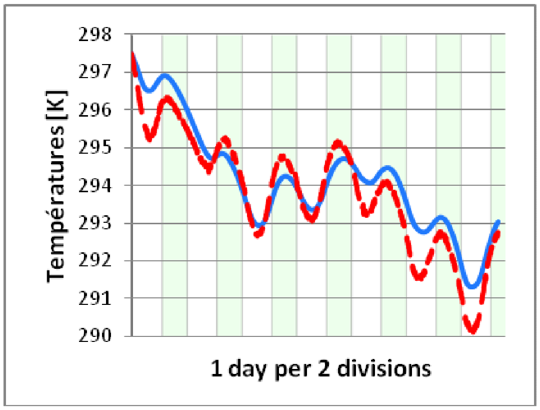

Figure 5: temperature on top of the insulation layer- heavy roof, semi intensive vegetation

Figure 5 shows the temperature measured and calculated on the top of the insulation layer. The measurements show a very small temperature variation between the night and day periods. This is also well represented by the model showing that the solar flux is partially tackled by the evapo-transpiration phenomena. The soil layer contributes also to the thermal inertia of the roof.

4.2. Extensive green roof with a concrete structure

Figure 6 shows the measured and calculated temperature on the top of the insulation layer. In the case of the extensive green roof, the soil layer is small which creates a smaller thermal inertia. This is observed by a higher temperature difference between the day and night period.

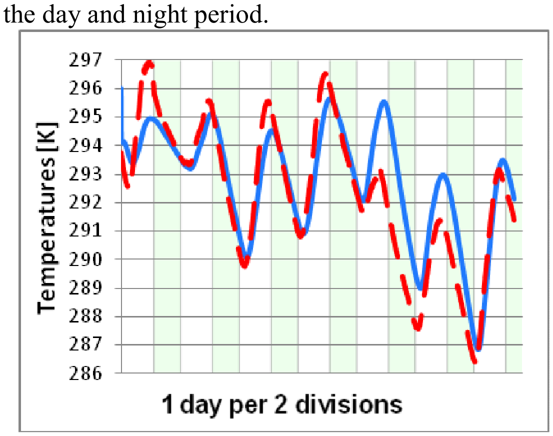

Figure 6: temperature on top of the insulation layer- heavy roof, extensive vegetation

4.3. Comparison between the different tested roofs

Thermal confort in a house is improved when temperature differences between different walls is low. Roof is collecting the solar flux and presenting high temperatures during the day period. Reducing this temperature plays a very important role in the thermal confort improvement leading to less air conditioning energy consumption.
Table 1 shows the temperature under the insulation layer for the different tested roofs.

Table 1: Temperature evolution under the insulation layer and day/night differences

Roof	Maximum		Minimum		Temperature difference	
	Measured	calculated	Measured	Calculated	Measured	Calculated
Light roof without vegetation	28.1°C	27.5°C	14.3°C	15°C	13.8°C	12.5°C
Light roof with an extensive vegetation	25.5°C	24°C	14.5°C	16.6°C	11°C	7.4°C
Heavy roof without vegetation	22.8°C	22.6°C	18.1°C	18.2°C	4.7°C	4.4°C
Heavy roof with an extensive vegetation	21.9°C	22.6°C	18.5°C	18.6°C	3.4°C	4°C
Heavy roof with a semi intensive vegetation	23.5°C	22.7°C	19.3°C	19.2°C	4.2°C	3.4°C

Light roofs without vegetation present the highest temperature during the day period. It also presents the highest temperature difference between the day and night period. The use of extensive vegetation reduces this temperature by 3 K.

In case of heavy roof, the thermal inertia of the concrete permits to reduce the maximal temperature and the day/night temperature difference. The vegetation impact in this case is very low.

6. CONCLUSIONS

This paper presents a model and an experimental comparison of the behavior of different roofs with and without vegetation.

The vegetation behavior is modeled and the comparison between the model results and the experimental ones permits to validate the model.

The comparison between the different tested roofs permits to draw some conclusions:

- Light roofs without vegetation present a high roof temperature leading to high thermal discomfort
- Use of vegetation on light roofs permits to improve the thermal comfort
- The humidity of the soil is a key parameter for the solar flux tackling
- In all the cases, with humid soil, the solar flux is nill

NOMENCLATURE

c_p	Specific heat capacity	J/kg K	**Subscripts**	
D	Diffusion coefficient	m^2/s	air	Ambiant air
D_{vT}	Vapor diffusivity	$kg.m^2/sK$	can	Canopy
h	Heat transfer coefficient	W/m^2 K	conv	Convection
	Specific enthalpy	J/kg	fc	Field capacity
RH	Relative humidity	_	sto	Stomata
I	Solar Flux	W/m^2	vap	Vapor
k_0	Extinction coefficient	_	veg	Vegetation
K	Hydraulic conductivity	m/s	wp	Wilting point

LAI	Leaf area index	_
L	Latent heat of vaporization	J/kg
S	Surface area	m²
SN	Index of nudity of soil	_
P_{clim}	Function of time of year (P_{clim} = 0 during the growing season)	_
P_{sat}	Saturation water vapor pressure	Pa
r	Mass transfer resistance of the vegetation leaves	s/m
R_v	Gas constant	J/mol K
T	Temperature	K
α	Absorption coefficient	_
	Thermal diffusivity	m²/s
γ	Psychometric constant	Pa/K
ε	Emissivity	_
τ	Transmittance	_
ε_p	Porosity	_
λ	Thermal conductivity	W/m² K
ρ	Density	kg/m^3
ψ	Moisture potential	m
ω	Absolute humidity	kg_{vapor}/kg_{air}

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